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Simulation/Design Validation Technology

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Summary

Simulation plays an increasingly important role in the development of new missile systems. This paper contains a brief overview of the various types of simulation models used in different phases of design and evaluation. The main emphasis is placed on trajectory simulation models. The usefulness of different trajectory models for different purposes is treated. A recommendation is to avoid using more complicated models than are required to address the problem of interest. The problem of using a very limited number of test firings to validate a highly complex model is mentioned.

Introduction

In the design of a new missile system, as well as in the development of tactics, modelling and simulation plays an increasingly important role. The main reason for this is, of course, to save money. The number of test firings, which are expensive, has declined and more of the system validation is now done using simulations. An example of this is given in table 1.

Modelling and simulation is a concept that includes many different aspects. Modelling and simulation of missiles can be used for many different purposes, e.g.:
- Concept studies and preliminary design
- System design
- Verification of system performance
- Assessment and analysis of systems
- Assessment and development of tactics
- Training of operators
- Threat assessment

Usually the models used in early design studies done by industry or in early studies by the government to define requirements are much simpler than the models used for final design and requirement verification.

In the development of a missile system it is common to develop a hierarchy of models from small subsystems to the entire system. All models are based on equations describing the relevant physical phenomena and on data describing the studied missile system.

Issues of vital importance to all models are verification and validation. Verification is the process to assure that the simulation programme is a true representation of the underlying physical model, while validation is the process to assure that the model is a good representation of reality, given the questions to be treated by the model.

The most relevant models for assessment of missile system performance and the transfer of data between the models are outlined in figure 1. The following text will mainly concentrate on trajectory simulation, missile system design, and verification of system performance.

Trajectory Models

Trajectory simulation models can differ widely in complexity. They can be categorised according to several principles:
- 2D or 3D
- Linear or non-linear
- Kinematic or dynamic
- All digital or hardware-in-the-loop
- One-on-one or many-on-many

Practically all possible combinations given by the above alternatives can be used.

Below follows a discussion first on various types of one-on-one models and then on many-on-many models, mainly focused on the difficulties with choosing the correct measures of effectiveness (MoE). Textbooks on trajectory models include Zarchan.

2D or 3D Model

As a 2D model is significantly easier both to develop and to use, it must be recommended to start the modelling and simulation work with a 2D model. Further reasons for using 2D models are that in many cases most of the motion takes place in a plane and also that many roll stable missiles have weak cross coupling between the channels.

Linear or Non-Linear

A missile model is highly non-linear in many of its parts. Yet linear models are often used for analysis and design. Advantages from using linear models include:
- Smaller model
- Super positioning applies, i.e. disturbances can be treated separately and their effects can be added.
- Standard design tools can be used for controller design.
- The method of adjoints can be used to calculate the effects of stochastic disturbances in an analytical way, thus avoiding the use of multiple Monte Carlo simulations.

Although linear models play an important part of controller design, more complex non-linear models have to be used to assess the performance of the missile and the control system.

Modern software, such as Matlab/Simulink, allows rapid linearisation of complex non-linear systems and provides an environment for design and simulation.

Kinematic Models

A kinematic model is a model where motion takes place, but where the cause of the motion is not treated, i.e. the dynamics is not included. In a missile model this means that the missile follows an ideal trajectory according to the guidance law unless some imposed limits, such as maximal range, are reached.

Kinematic models can be used to obtain launch and intercept zones. Kinematic models do, however, not provide any miss distance.

Required data for a kinematic model include:
- Basic aerodynamics
- Thrust
- Guidance law
- Limitations such as
  - Maximal time of flight
  - Minimal velocity
  - Maximal angle of attack

    –   Maximal load factor
    –   Minimal closing velocity (for fusing)
    –   Field of view of command receiver or seeker
    –   Maximal tracking angular velocity

A launch zone, which is a typical result given by several runs of a kinematic model is shown in figure 2. Kinematic models can also be used to calculate no-escape zones. A no-escape zone is the subset of the launch zone, where a launched missile is guaranteed to hit even if the target evades with maximal acceleration. An example of a no-escape zone is given in figure 3.

The limited amount of data required by kinematic models make them well suited for preliminary analysis in the early stages of design and also for analysis of foreign, potentially hostile, systems.

Dynamic Models

A dynamic model calculates the trajectory of the missile using Newton's equations of motion for a rigid body.

A dynamic model requires detailed data such as:
- Aerodynamics
- Thrust
- Guidance and control system
- Disturbances, e.g. measurement noise

The output from a dynamic model consists of time records of all variables, including the missile trajectory and also the point of impact or tile miss distance.

Dynamic models always contain transformations between coordinate systems. The missile dynamics is normally calculated in a missile body-fixed coordinate system. The missile velocities obtained in the body-fixed system are then transformed to an earth-fixed system where they are integrated to positions.

Hardware-in-the-loop

Even though computer models have progressed very rapidly over the last decades, there is still a need for hardware-in-the-loop (HWIL) simulation. In HWIL simulations the normal approach is to use real hardware for the seeker in the missile and to use software to simulate the fly out of the missile. The seeker is mounted on a turn table in a room where the background signature can be carefully controlled (an anechoic chamber in the case of radar seekers). A target scenario is displayed for the seeker and the seeker output is fed into a digital model where the dynamics of the missile are simulated. The motion of the missile is then fed to the turn table, such that the seeker is moved in accordance to the simulated missile motion.

Many-on-many

For assessments at a higher systems level many-on-many models are often used. A many-on-many model treats scenarios with more than one weapon on each side.

Assessment on higher levels is far more complicated than assessment on a one-on-one basis. The main reasons for this are that the system to be assessed contains not only technology but also humans and decision making, and also that it is much less clear what constitutes success.

An example of the difficulties of defining success can be taken from the Gulf War. The US Patriot surface-to-air missile was used to defend against attacking Scud missiles. The post war analysis has shown that the Patriots had very little, if any, effect on the incoming warheads. To conclude from this that the Patriot had no effect in the war is to make a severe error. Through television, millions of people all over the World could follow the Patriot missiles as they rose to the skies to ward off the incoming danger. By deploying Patriots to Saudi Arabia and Israel the US clearly showed concern for her allies' security. The conclusion is therefore that the Patriot had great effect, despite perhaps not scoring a single kill.

A further example of difficulties associated to many-on-many assessment can be taken from Berglund and Hansson. An assessment was made of a proposal to purchase a new and much improved surveillance radar to the Swedish Hawk surface-to-air missile system. The old system, called RBS77, had an old 2D radar with somewhat limited performance, while the proposed new system (RBS87) had a modern 3D radar with much better performance, not least in an environment with electronic warfare. The two systems were assessed in a many-on-many model, where several scenarios were used. The aggressor employed different weapons (iron bombs, guided missiles, stand-off weapons) and tactics (low or high altitude, defence suppression or not etc). All the scenarios were run with or without enemy use of electronic warfare. When the number of killed enemy aircraft was summed up, the result was according to table 2.

The surprising results motivated a closer look on the simulation results, which showed that the main reason for the results was that the main effect of the electronic jamming was to reduce the range of the surveillance radar. The reduced detection range resulted in missile launch at shorter range and consequently shorter times of flight. However the kill ratio per launched missile increased as the shorter time of flight resulted in less time for enemy counter measures such as manoeuvres. As most of the scenarios provided a target rich environment, the final result of the low performance radar and the enemy jamming was a high kill ratio. A conclusion is that kill ratio not was a good measure of effectiveness for assessment of the value of the modern radar.

A conclusion from the above example is also that great emphasis should be placed on the formulation of scenarios to reflect the questions to be treated and that the use of overly large and complicated models should be avoided. Qualified analysts are also needed throughout the process.

The choice of measure of effectiveness is further complicated by the changing nature of armed conflicts. While it was fairly straight forward to assess effectiveness in the major war that was envisioned during the Cold War, it is much more complicated in the broader range of conflicts envisioned today. Present and future conflicts are likely to take place in a peace time environment, where much of the focus is on public opinion and media relations. A weapon of today must not only disable the enemy, it must avoid collateral damage and it must also look good on television.

So far there has not been established any new set of relevant measures of effectiveness to reflect asymmetrical conflicts in a peace time environment.

Performance verification

As was previously mentioned simulation models play a major part in the process of performance verification.

Presently there does not exist any established theory for how to verify the performance of a highly complex system given only a few real test firings and simulations. Some of the problems facing those working with verification and some of the present practice are outlined below.

In the development of a missile system the real physical system is usually developed in parallel with simulation models. This process is described in figure 4, perhaps following a more logical bottom up approach than is usually the case.

A detailed 6 degree of freedom trajectory simulation model is developed. The detailed model either contains detailed models of subsystems, such as the seeker, or simpler descriptions based on detailed submodels. The models of the subsystems are in each case validated against experiments and tests. A hierarchy of models is thus developed and the general hope is that models based on validated submodels have a good chance of being good representations of reality.

The number of real system tests, i.e. live test firings, is normally very small, perhaps less than 10. Data from the test firings are recorded and used both as a basis for model validation and as a basis for system performance verification. Simulations of the exact test firings are conducted and a comparison with the test

firings is made. The purpose of the comparison is to validate the model, but often some changes have to be added to the model. The model is then to be declared as valid, often by a government agency.

The next step is to use the model to simulate a large number of scenarios and to use the simulation results to verify system performance.

In this process of model validation and system performance verification there are many unsolved problems:
- How should a comparison between live firings and performance requirements be conducted given statistical properties and measurement quality?
- How should the live firings be compared to post-test simulations given statistical properties and measurement quality?
- Is it possible to use the test-firings both to update the model and to validate it?
- How should the scenario for the test firings be chosen?
- How many test firings are required given the complexity of the system?
- How should the results from test firings and simulation be compared to the performance requirements in order to verify the system performance?

As these questions currently remain unanswered it must be concluded that validation and verification despite great efforts still relies, at least to some extent, on faith. However, as experience shows that reasonable results are achieved through this process, there seems to be reasons to have faith.

References

Assarsson A (ed.), *Robotkurs*, Defence Research Establishment, Stockholm, Sweden, 1996. (In Swedish)

Berglund E and Hansson MB, "Swedish experiences from air defense models", AIAA Paper 99-4025 presented at *AIAA Modeling and Simulation Technologies Conference*, Portland, Aug. 9-11, 1999.

Zarchan P, *Tactical and Strategic Missile Guidance*, Washington, DC: American Institute of Aeronautics and Astronautics, 1994.

Table 1. Number of test firings during development and evaluation. (Data from British Aerospace)

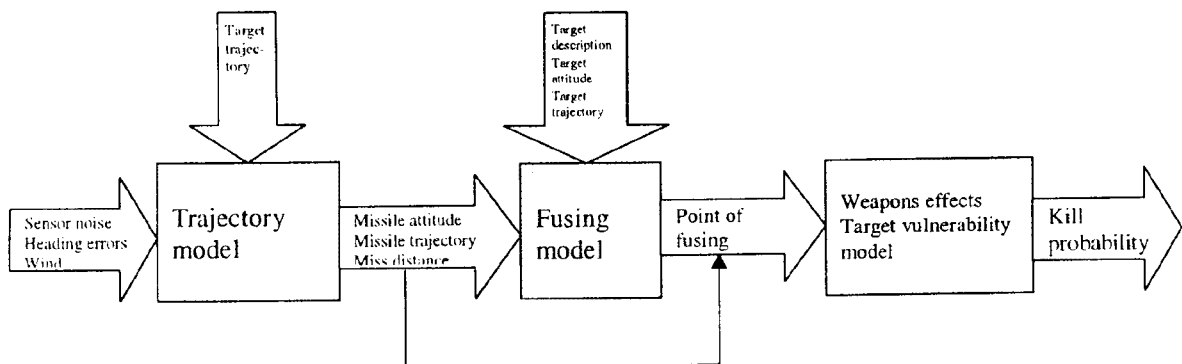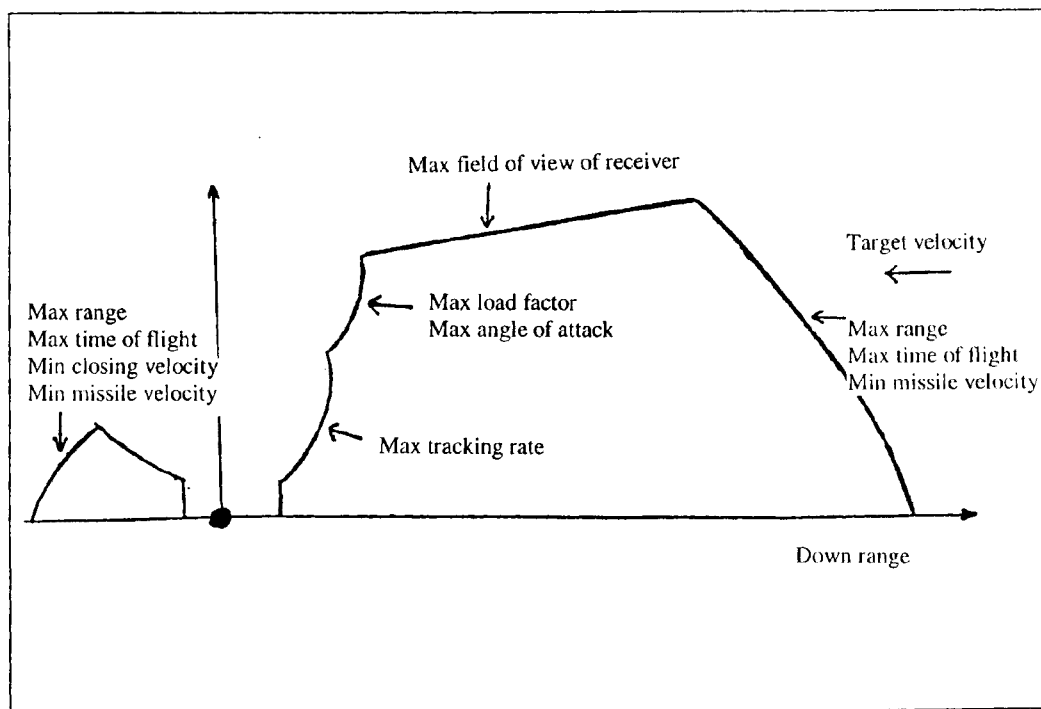| Year	Missile	Development	Evaluation	Total test firings	Simulation model
1951-58	Firestreak	209	94	303	None
1957-66	Red Top	77	40	117	Analog
1964-72	Martel	24	27	51	Hybrid
1973-78	Sky Flash	12	10	22	Digital

Figure 1. Models for missile system assessment.

Figure 2. Launch zone for a typical line-of-sight guided surface-to-air missile. The limiting factors are noted.
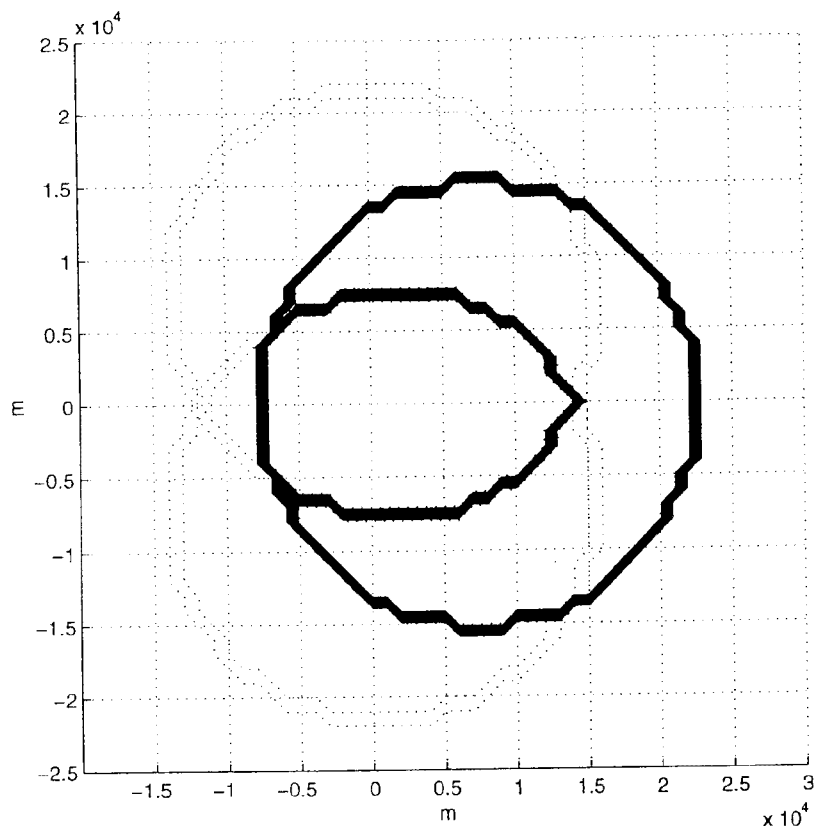

Figure 3. Example of no-escape zone (inner zone) and launch zone against a straight and level target for a surface-to-air missile using proportional navigation.

Table 2. Kill ratios in scenarios with and without electronic warfare.

	Kill ratio without enemy EW	Kill ratio with enemy EW
Old RBS77	59%	53%
New RBS87	58%	42%

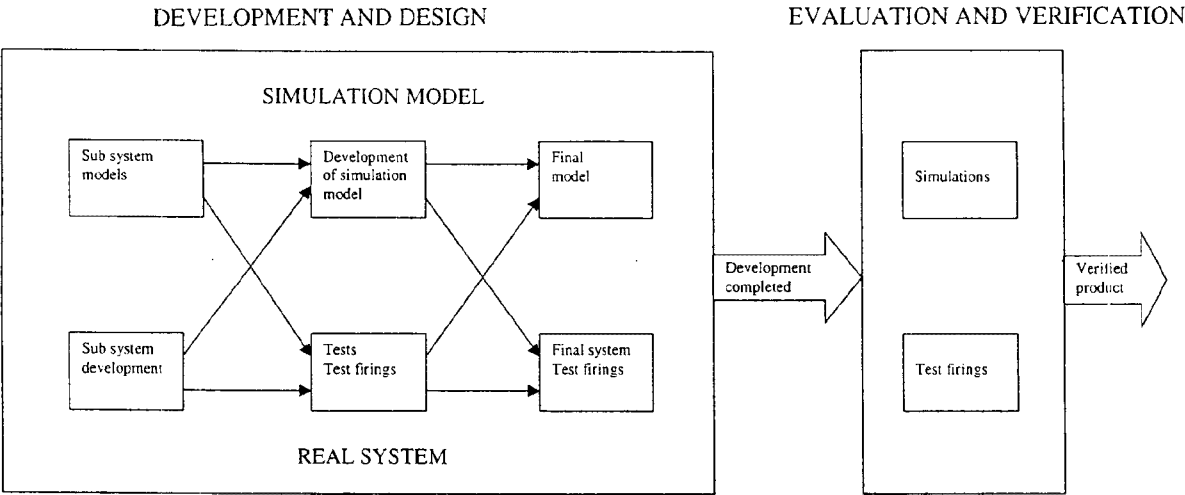DEVELOPMENT AND DESIGN   EVALUATION AND VERIFICATION

Figure 4. The principal development of real system and simulation models for system design and performance verification.

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